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Thermal indoor environment and energy consumption in a plus-energy house: cooling season measurements

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Abstract

The present study is concerned with the thermal indoor environment and HVAC system energy consumption of a detached, one-story, single family, plus-energy house during a cooling season. The house was located in Denmark and it has been used as a full-scale experimental facility for one year. The house was cooled by a floor cooling system and was ventilated with a mechanical ventilation system. Different operative temperature set-points and different ventilation rates were tested. Operative temperature at a representative location inside the occupied zone was used as an indicator of the thermal indoor environment. For the energy consumption of the HVAC system, air-to-brine heat pump, mixing station and controller of the radiant floor, and the air handling unit were considered.

The measurements were analyzed based on the achieved indoor environment category (according to EN 15251:2007), overheating hours (according to DS 469:2013) and the energy consumption. Operation and switchover of the heating and cooling system during the transition periods (i.e. May and September) proved to be a challenge. Overheating was a significant problem. Decreasing the operative temperature set-point (of the floor cooling system) and increasing the ventilation rate provided a better thermal indoor environment but with increased energy consumption. The thermal indoor environment and energy performance of the house can be improved with decreased glazing area, increased thermal mass, installation of solar shading, adjustment of the orientation of the house, and natural ventilation.

Keywords: full-scale measurement; plus-energy house; energy consumption; thermal indoor environment; overheating; floor cooling; transition period

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1. Introduction

The building energy codes are becoming tighter and nZEB (nearly zero-energy building) levels are being dictated for new buildings by 2020 in the European Union [1]. One commonly encountered problem in low-energy and passive houses is overheating. Overheating has been reported from different countries such as Denmark by Larsen and Jensen [2], and from Sweden by Janson [3]. Some of the main reasons of overheating are large glazing areas, poor (or lack of) solar shading, lack of ventilation [4], lack of thermal mass, and lack of adequate modeling tools [5].

Some characteristics of the house considered in this study (large glazing areas, low thermal mass and so forth) were similar to other houses where overheating was observed, therefore this study focuses on the thermal indoor environment (considering also overheating and HVAC system energy consumption) during a cooling season (May to September 2014) in a detached, one-story, single family, plus-energy house [6], located in Bjerringbro, Denmark. The house has been operated for one year and different heating [7] and cooling strategies were tested. The overall thermal indoor environment and overheating were evaluated based on EN 15251:2007 [8] and DS 469:2013 [9], respectively.

2. Description of the house and its HVAC system

The studied house was a single family, detached, one-story house with a floor area of 66.2 m^2 and a conditioned volume of 213 m^3. Interior of the house consisted of a single space combining kitchen, living room and bedroom. Shower and toilet areas were separated from the main indoor space by partitions. The technical room was completely isolated from the main indoor space, and had a separate entrance. The wall between the technical room and the indoor space was insulated with the same insulation level as the envelope.

The house was constructed from wooden elements. The walls, roof and floor structures were formed by installing prefabricated elements in a sequential order, and the joints were sealed. The North and South glazing façades were inserted later and the joints between the glazing frame and the house structure were sealed. The glazing façades in the North and South were partly shaded by the overhangs. No solar shading was installed in the house except for the skylight window. All windows had a solar transmission of 0.3. The largest glazing façade was oriented to the North with a 19° turn towards the West. The exterior views of the house may be seen in Fig. 1:

Fig. 1. Exterior views of the house, seen from North-West (left) and South-West (right).

The surface areas and thermal properties of the structural elements of the house are given in Table 1:

Table 1. Thermal properties of the envelope.

	North	South	East	West	Floor	Ceiling
Walls, Area, [m^2]	-	-	37.2	19.3	66.2	53
Walls, U-value, [W/m^2K]	-	-	0.09	0.09	0.09	0.09
Windows, Area, [m^2]	36.7	21.8	-	-	-	0.74
Windows, U-value, [W/m^2K]	1.04	1.04	-	-	-	1.04

The sensible cooling of the house relied on high temperature cooling via the hydronic radiant system in the floor. The floor cooling system was a dry radiant system, consisting of a piping grid installed in the wooden layer, with aluminum profiles on the pipes for better thermal conductance. The details of the floor system were: chipboard system, with aluminum heat conducting profiles (thickness was 0.3 mm and length was 0.17 m), PE-X pipe, 17x2.0 mm. Pipe spacing was 0.2 m. A wooden floor covering was used with a thickness of 14 mm and a thermal conductivity of 0.13 W/mK. In total there were four loops in the floor. The available floor area for the embedded pipe system installation was 45 m^2, and the cooling capacity of the floor cooling was 27.1 W/m^2.

The heat sink of the house for space cooling was air, realized by means of a reversible air-to-brine heat pump. There was a flat plate heat exchanger between the hydronic radiant system and the air-to-brine heat pump. The part between the heat exchanger and the heat pump was filled with an anti-freeze mixture (40% ethylene glycol).

A mixing station (and a controller), that links the radiant system with the heat sink, was installed to control the flow to each loop, and the supply temperature to the radiant system. The operation of the radiant system was based on the operative temperature set-point that was adjusted on a room thermostat (a matt gray half-sphere) with 0.5°C intervals and on the relative humidity inside the house (to avoid condensation).

The mechanical ventilation was only used to provide fresh air into the house since the main sensible heating and cooling terminal was the radiant system. Fresh air was provided by an air handling unit, AHU, which had passive and active heat recovery possibilities (to avoid too low or too high supply air temperatures). The passive heat recovery was obtained by a cross-flow heat exchanger, with an efficiency of 85% (sensible heat). By-pass was possible. The AHU could supply air at a flow rate up to 320 m^3/h at 100 Pa. The design ventilation rate was 0.5 ach.

3. Materials and methods

The house was used as a full-scale experimental facility from October 2013 to October 2014. There were no occupants living in the house but the occupants and equipment (internal heat gains) were simulated by means of heated dummies. A dummy is a circular aluminum duct, with a diameter of 0.22 m and a height of 1 m. It had closed ends and an electrical heating element (wire) was installed on the internal surfaces of the duct. Dummies had an adjustable heat output up to 180 W [10].

The occupancy and equipment schedules were adjusted with timers. Two dummies were used to simulate the occupants at 1.2 met (ON from 17 to 08 on weekdays and from 17 to 12 on weekends), one dummy (equipment #1, 120 W, 1.8 W/m^2) was always ON to simulate the house appliances that are always in operation, the fourth dummy (equipment #2, 180 W, 2.7 W/m^2) was used to simulate the house appliances that are in use only when the occupants are present and the fifth dummy was used to simulate the lights (180 W, 2.7 W/m^2, ON from 06 to 08 and from 17 to 23 until 27/05/2014, and after this date, ON from 20 to 23 every day). The house had ceiling mounted lights ON from 21 to 23 every day (140 W, 2.1 W/m^2). Additionally, there was a data logger and a computer (80 W, 1.2 W/m^2), and a fridge (30 W, 0.4 W/m^2) which were always ON.

During the measurements, overheating proved to be a problem. To tackle this problem, manually operated internal solar shading (manufacturer provided g-value was 0.19) was installed on the North façade, covering 20 m^2, on 30/07/2014 and it was used in fully down position until the end of the experiments. The house was not cooled from 20/06/2014 to 23/06/2014 (the floor cooling and the AHU were OFF), due to a repair in the HVAC system.

Various physical parameters and energy consumption were measured during the experimental period. The air and globe temperatures were measured at the heights of 0.1 m, 0.6 m, 1.1 m, 1.7 m, 2.2 m, 2.7 m, 3.2 m and 3.7 m at a central location in the house (occupied zone). The globe temperatures were measured with a gray globe sensor, 4 cm in diameter. This sensor has the same relative influence of air- and mean radiant temperature as on a person [11] and, thus, at 0.6 m and 1.1 m heights will represent the operative temperature of a sedentary or a standing person, respectively. The air temperature sensor was shielded by a metal cylinder to avoid heat exchange by radiation [12]. The output from the sensors was logged by a portable data logger.

The energy consumptions of the air-to-brine heat pump, mixing station, and the controller of the radiant system were measured with wattmeters. The energy consumption of the AHU was measured through a branch circuit power meter (BCPM).

A panoramic view of the interior of the house, the measurement location and the sensors used for the measurements may be seen in Fig. 2:

Fig. 2. The interior of the house (left), the measurement location (middle) and the globe and air temperature sensors (right).

4. Experimental settings

During the cooling season, the house was cooled by floor cooling and was ventilated with a mechanical ventilation system (heat recovery on ventilation). Different operative temperature set-points (to control the operation of the radiant system) and different ventilation rates were implemented. The most important boundary conditions regarding different cases in cooling season are given in Table 2 (HV: higher ventilation rate, S: solar shading):

Table 2. Periods and experimental settings of the case studies.

Period	Average external air temperature, [°C]	Floor cooling set-point, [°C]	Ventilation type and ventilation rate	Solar shading	Case study abbreviation
1st of May to 27th of May*	14.7	20**	Heat recovery, 0.5 ach	No	FH20
27th of May to 19th of June	18.7	25	Heat recovery, 0.5 ach	No	FC25
19th of June to 13th of July	18.7	25	Heat recovery, 0.8 ach	No	FC25-HV
13th of July to 30th of July	22.7	24	Heat recovery, 0.8 ach	No	FC24-HV
30th of July to 21st of Aug	18.1	24	Heat recovery, 0.8 ach	Yes	FC24-HV-S
21st of Aug to 1st of Oct	16.0	24	Heat recovery, 0.5 ach	Yes	FC24-S

*: The dummies simulating the occupants and a dummy (equipment #2) were OFF during this experimental period. **: Floor heating was active, transition period.

5. Results and discussion

The performance of different cooling strategies was evaluated based on the indoor environment categories given in EN 15251:2007 for sedentary activity (1.2 met) and clothing of 0.5 clo. In addition, the hours above 26°C and 27°C were calculated following DS 469:2013. According to DS 469:2013, 26°C should not be exceeded for longer than 100 hours during the occupied period and 27°C should not be exceeded for longer than 25 hours. The obtained indoor environment categories, and hours above 26°C and 27°C with respect to the cooling strategy are given in Table 3, and the operative temperature and external air temperature over the cooling season are presented in Fig. 3:

Table 3. The category of indoor environment based on operative temperature (at 0.6 m height).

Indoor environment category/case	FH20	FC25	FC25-HV	FC24-HV	FC24-HV-S	FC24-S	Total, average
Category 1 (23.5-25.5°C)	52%	56%	36%	54%	39%	22%	41%
Category 2 (23.0-26.0°C)	73%	72%	49%	72%	58%	36%	57%
Category 3 (22.0-27.0°C)	87%	87%	75%	91%	84%	72%	81%
Category 4	13%	13%	25%	9%	16%	28%	19%
Hours above 26°C	48	129	79	87	7	0	350
Hours above 27°C	19	71	38	34	0	0	162

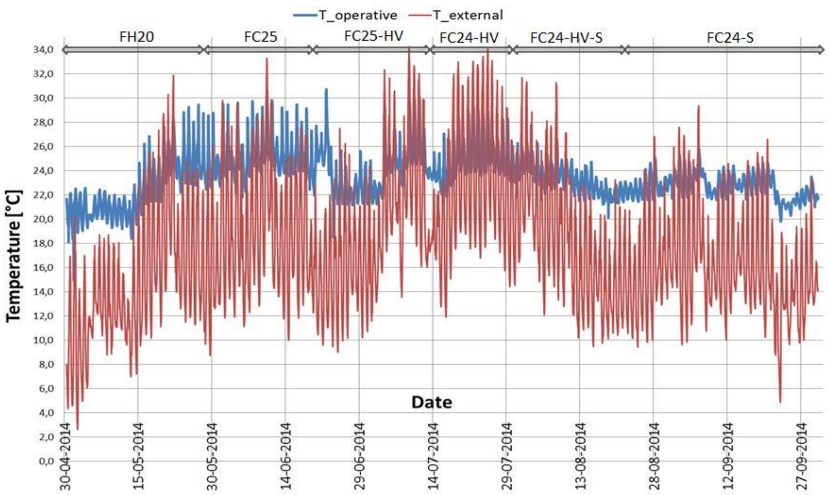

Fig. 3. Operative temperature (at 0.6 m height) and external air temperature during the cooling season.

It could be seen from Table 3 and Fig. 3 that the operative temperature was 57% of the time in Category 2 and 19% of the time outside the recommended categories in EN 15251:2007. This was mainly due to the transition periods and due to overheating. The hours above 26°C and 27°C exceeded the values recommended in DS 469:2013. Decreasing the operative temperature set-point and increasing the ventilation rate helped to address the increased cooling load, but with a higher energy consumption.

The results also show that even though the floor heating was active during most of May (transition month), floor cooling could have been activated in the second half of May, which would have reduced the hours above 26°C and 27°C, and improved the performance regarding indoor environment.

The most significant problems of the house were the large glazing façades (including the lack of solar shading) and the lack of thermal mass in order to buffer the sudden thermal loads. The direct solar radiation from the South façade was not a problem, because of the orientation, longer overhang and because of the trees that created shadows on the South façade. The most of the overheating hours were in the late afternoon (i.e. from 18:00 until the sunset); during this period of the day, there was direct solar radiation coming into the house from the North façade.

For the HVAC system's energy consumption, air-to-brine heat pump, mixing station, controller (controls the flow into the radiant systems' loops), and AHU were considered. The set-point of the heat pump was 15°C. The energy consumption of the components as a function of different cases is presented in Table 4:

Table 4. Energy consumption of the HVAC system components during the cooling season.

Case	Heat pump [kWh]	Mixing station [kWh]	Controller, radiant system [kWh]	AHU [kWh/day]	Total [kWh]	Total [kWh/day]
FH20	206.4	1.3	0.4	1.6	250.7	9.3
FC25	95.4	5.4	1.8	1.6	138.7	6.0
FC25-HV	110.1	3.2	1.4	3.1	189.8	9.0
FC24-HV	114.8	6.7	2.0	3.6	184.3	10.8
FC24-HV-S	105.6	3.8	1.2	3.6	189.3	8.6
FC24-S	145.9	0.6	0.2	1.6	212.4	5.3

The results show that the increased ventilation rate and lowered operative temperature set-point increase the energy consumption. This is an expected behavior due to higher power input to the fans in the AHU and longer operation time of the pump of the floor cooling system. The increased energy consumption contributes to a better thermal indoor environment but more energy efficient strategies should be used to decrease the cooling demand and to address the necessary cooling demand with energy efficient measures, hence decrease the energy consumption (e.g. lower ventilation rates when the house is unoccupied, natural ventilation when the outside conditions are suitable, higher thermal mass, decreased glazing area, solar shading, a better orientation of the house and so forth).

The transition periods (i.e. September and May) require careful consideration regarding the operation of the heating and cooling system and regarding the switchover between heating and cooling operation. Though, increased thermal mass could address some of the concerns regarding thermal indoor environment and energy consumption during the transition periods.

6. Conclusion

A plus-energy, single family house was operated with different cooling strategies throughout a cooling season. The operative temperature at a central location in the occupied zone was used to evaluate the thermal indoor environment. The energy consumption of the HVAC system was also measured and analyzed.

It was observed that the operation of the heating and cooling system during the transition periods was problematic and it affected the thermal indoor environment significantly. Cooling demand of the house was high due to the large glazing façades (including the lack of solar shading) and the lack of thermal mass in order to buffer the sudden thermal loads.

The operative temperature was in Category 1 for 41%, in Category 2 for 57%, in Category 3 for 81% and in Category 4 for 19% of the time, according to EN 15251:2007. Overheating was a significant problem; the operative temperature was higher than 26°C for 350 hours and higher than 27°C for 162 hours, exceeding the values recommended in DS 469:2013. These results indicate that an improvement is necessary.

Increasing the ventilation rate and decreasing the operative temperature set-point helped to achieve a better thermal indoor environment but at the cost of increased energy consumption. Because of the high cooling demand, these solutions were not enough to avoid overheating. Therefore other means (which will decrease the cooling demand) would be more effective than increasing the ventilation rate and lowering the temperature set-point. Some of these means are decreased glazing area, increased thermal mass, installation of solar shading, and adjustment of the orientation of the house.

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